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Diversified cropping systems in semiarid Montana: Nitrogen use during drought

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Abstract

Improved nitrogen use efficiency would be beneficial to agroecosystem sustainability in the northern Great Plains of the USA. The most common rotation in the northern Great Plains is fallow–spring wheat. Tillage during fallow periods controls weeds, which otherwise would use substantial amounts of water and available nitrogen, decreasing the efficiency of fallow. Chemical fallow and zero tillage systems improve soil water conservation, and may improve nitrogen availability to subsequent crops. We conducted a field trial from 1998 through 2003 comparing nitrogen uptake and nitrogen use efficiency of crops in nine rotations under two tillage systems, conventional and no-till. All rotations included spring wheat, two rotations included field pea, while lentil, chickpea, yellow mustard, sunflower, and safflower were present in single rotations with wheat. Growing season precipitation was below average in 3 of 4 years, resulting in substantial drought stress to crops not following fallow. In general, rotation had a greater influence on spring wheat nitrogen accumulation and use efficiency than did tillage system. Spring wheat following fallow had substantially higher N accumulation in seed and biomass, N harvest index, and superior nitrogen use efficiency than wheat following pea, lentil, chickpea, yellow mustard, or wheat. Preplant nitrate-N varied widely among years and rotations, but overall, conventional tillage resulted in 9 kg ha^{-1} more nitrate-N (0–60 cm) for spring wheat than did zero tillage. However, zero tillage spring wheat averaged 11 kg ha^{-1} more N in biomass than wheat in conventional tillage. Nitrogen accumulation in pea seed, 45 kg ha^{-1}, was superior to that of all alternate crops and spring wheat, 17 and 23 kg ha^{-1}, respectively. Chickpea, lentil, yellow mustard, safflower, and sunflower did not perform well and were not adapted to this region during periods of below average precipitation. During periods of drought, field pea and wheat following fallow had greater nitrogen use efficiency than recropped wheat or other pulse and oilseed crops.

Keywords: Spring wheat; Field pea; Chickpea; Lentil; Yellow mustard; Safflower; Sunflower; Zero tillage; Soil nitrate; Nitrogen recovery index; Nitrogen harvest index; Crop yields

1. Introduction

Available water and nitrogen typically are the most limiting factors for dryland crop production in semiarid environments (O'Leary and Connor, 1997b). Conventional summer fallow usually increases both stored soil water and nitrate-nitrogen for subsequent crop use. Summer fallow, however, is inefficient for precipitation storage, with about 25% of precipitation storage efficiency (as reviewed in Farahani et al. (1998)), but intensification of crop production, by reduction of summer fallow acreage, provides more efficient utilization of the scarce water resource in the semiarid

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central Great Plains (Farahani et al., 1998). The adoption of zero tillage systems has allowed for intensification of production in semiarid regions due to improvements in water use and water use efficiency (Hatfield et al., 2001). Research in diverse regions, including Victoria, Australia (O'Leary and Connor, 1997b; Cantero-Martinez et al., 1999), and Nebraska (Lyon et al., 1998) and Texas, USA (Baumhardt and Jones, 2002) suggest zero tillage improved soil water storage compared to conventional tillage. In contrast, Lenssen et al. (2007) documented the large, positive impact of summerfallow on subsequent spring wheat productivity and water use efficiency during drought in the northern Great Plains.

Soil nitrate availability is highly important because of its necessity for crop production. However, nitrate can be an important environmental contaminant due to its high potential for leaching into surface or ground waters. For improved environmental health and soil quality, producers are encouraged to diversify away from monocultures, primarily wheat (*Triticum aestivum*), and to reduce residual nitrate and the extent of land left in fallow (Matson et al., 1997; Struik and Bonciarelli, 1997; Gregory et al., 2002).

Improved nutrient use efficiency, particularly for N, is an important goal in cropping system development (Karlen et al., 1994). Huggins and Pan (2003) showed determination of key indicators of nitrogen use efficiency in cereal-based agroecosystems enabled broad assessment of agronomic management and environmental factors related to N use. Key indicators of nitrogen use efficiency included grain yield and N accumulation, N in aboveground biomass, N harvest index, and grain N accumulation efficiency.

The successful inclusion of pulse and oilseed crops preceding cereals is now well documented in several dryland environments. Thomson et al. (1997) showed that white lupine (*Lupinus albus*), blue lupine (*L. angustifolius*), faba bean (*Vicia faba*), and field pea (*Pisum sativum*) produced satisfactory seed yields following wheat in Western Australia. In Saskatchewan, Canada, Miller et al. (2002a, 2003a,b) documented that field pea, lentil (*Lens culinaris*), and chickpea (*Cicer arietanum*) were productive crops in sequences with spring wheat. Unkovich and Pate (2000) reviewed recent literature on symbiotic nitrogen fixation by annual legumes, and concluded that pea generally fixed more N than lentil or chickpea. In a review of Australian research, Evans et al. (2001) concluded that blue lupine and field pea typically had positive effects on nitrogen balances. Additionally, Miller et al. (2002b) and Gan et al. (2003) documented increased grain yield and protein of spring wheat following pulses compared to spring wheat following spring wheat.

Oilseed crops also are adapted to semiarid environments. In a recent review, Johnston et al. (2002) summarized research from the Canadian prairie and adjacent border states of the USA, concluding that flax (*Linum usitatissimum*), mustards (*Brassica juncea* and *Sinapis alba*), and canola (*Brassica* sp.) were well adapted to cropping systems in the northern Great Plains. They also concluded that sunflower (*Helianthus annuus*) and safflower (*Carthamus tinctorius*), crops with superior abilities to utilize deep soil nitrogen, were better adapted to the northern and central Great Plains of the USA, areas with warmer temperatures and longer growing seasons than the Canadian prairie.

In Montana, the predominant crop in dryland systems is spring wheat. The predominant spring wheat (SW) production systems are summer fallow–SW and summer fallow–SW–SW with minimum tillage, typically a field cultivator equipped with 45-cm wide sweeps and rods. We developed a dryland cropping systems research project with considerable producer input, including various crop species and sequences. Overall, our objectives were to investigate the influence of tillage and cropping systems on crop productivity, soil quality, weed, arthropod and disease pests, and economic sustainability. Our experimental objectives were to determine N uptake and N use efficiency of spring wheat and alternate crops in conventional and diversified systems.

2. Materials and methods

2.1. Experimental site

The experimental site was located on a private farm (latitude 48°48′N, longitude 110°1′W, altitude 886 m a.s.l.), about 56 km WNW of Havre, Montana, USA. Long-term weather data for the specific research site were unavailable, and Havre is the nearest weather station. In 1999, a weather station was put in place at the research site for collection of weather data. Mean annual precipitation (1916–2003) at Havre was 305 mm, with about 233 mm occurring from April through September (Table 1). The average frost-free period is 128 days, 15 May to 20 September. The 22.7 ha research area, including alleys, was located in soil mapping associations of Kevin–Elloam clay loams (Kevin soil, 60% of area, fine-loamy, mixed Aridic Argiborolls; Elloam, 28% of area, fine, montmorillonitic Typic Natriboralfs; 2–8% slopes) and Scobey-Kevin clay loams (Scobey soil, 55% of area, fine, montmorillonitic Aridic Argiborolls; Kevin

Table 1
Long-term and annual monthly growing season precipitation

Month	Precipitation (mm) LT[a]	Year			
		2000[b]	2001[b]	2002[b]	2003[b]
April	24	12	10	3	36
May	45	24	13	36	28
June	65	49	21	112	38
July	38	10	10	27	5
August	31	3	23	43	24
September	29	29	0	25	33
Total (April–September)	232	127	77	246	164

[a] Long term (1916–2003) for Montana State University, Northern Agricultural Research Center, Havre, MT, located 56 km ESE of experimental site.
[b] Precipitation values at the experimental site located 56 km NWN of Northern Agricultural Research Center, Havre, MT.

soil, 30% of area; 0–4% slopes) derived predominantly from glacial till. Intensive soil sampling in April 1998 revealed average organic matter content was 1.2%, Olsen available phosphorus 10.9 mg kg^{-1}, exchangeable potassium 295 mg kg^{-1}, and pH were 7.4 for 0–15 cm depth.

The field area was in the Conservation Reserve Program from 1986 through 1997, with an undisturbed, mixed planting of crested wheatgrass (*Agropyron cristatum*) and alfalfa (*Medicago sativa*) to provide soil cover. Resident vegetation was sprayed twice in 1997 with formulated glyphosate to kill all established vegetation. Tillage was done with a field cultivator equipped with 45-cm wide sweeps prior to crop planting in spring 1998, but only on those plots designated to receive tillage. Tillage depth was about 7–8 cm.

2.2. Trial design

The experiment consisted of nine annual crop rotations and a planting of alfalfa with three perennial grasses, western wheatgrass (*Pascopyron smithii*), slender wheatgrass (*Elymus trachycaulus*) and green needlegrass (*Nassella viridula*). The nine annual crop rotations were (1) continuous spring wheat (SW), (2) fallow (F)–SW, (3) lentil–SW, (4) F–SW–SW, (5) F–SW–pea (P), (6) F–SW–safflower, (7) F–yellow mustard–SW, (8) F–chickpea–SW, and (9) sunflower–P–SW. The experimental design was a randomized complete block in a split plot arrangement. Whole plot treatment was tillage system, conventional with sweeps and rods or zero tillage. Subplots were individual components of the 10 sequences. Each phase of each rotation was present in four replications each year, for a total of 192 plots. Individual subplot size was 14.6 m× 30.4 m. The four ranges (replicates) were separated by 24.3 m wide alleys.

2.3. Crop management practices

Rates for fertilizer N application to spring wheat were based on yield goal of 2350 kg ha^{-1} of 13.5% protein spring wheat, totaling 118 kg N ha^{-1}. Residual nitrate-nitrogen, 0–60 cm, was subtracted from the overall N requirement for SW yield goal. Safflower, sunflower, and yellow mustard yield goals (total available N requirement) were 1500 (75), 1500 (75), and 1800 kg ha^{-1} (130 kg N ha^{-1}), respectively (Jacobsen et al., 2003). Each year, soil samples taken in late fall (mid-October) were analyzed for nitrate to 1.2 m in five increments, 0–15, 15–30, 30–60, 60–90, and 90–120 cm depths. Residual nitrate-nitrogen, 0–60 cm, was subtracted from total crop requirement. Nitrate content greater than 60 cm depth was not used in calculating nitrogen fertilizer requirement. A similar process was used for nitrogen fertilization of sunflower, safflower, and yellow mustard. As per Montana State University recommendations (Jacobsen et al., 2003), annual applications of phosphorus (11–52–0) and potash (0–0–60) were done for all annual crops at 56 and 48 kg ha^{-1}, respectively. Pulse crops were not fertilized with nitrogen fertilizer, other than the 11–52–0, except for lentil in 2003, which inadvertently received 20.6 kg N ha^{-1} as urea at planting. Preplant tillage and tillage of summer fallow plots was done with a standard field cultivator equipped with 45-cm wide sweeps mounted on C-shanks with attached coil-tooth spring harrows with 60 cm bars. Tillage depth was controlled by stabilizer wheels on the field cultivator frame. Tillage depth was to 7–8 cm. Regardless of tillage treatment, all fertilizers were banded at planting about 5 cm below and to the side of the seed row with a single-pass air seeder that fertilized and seeded a width of 3.66 m. Openers were a modified hoe type on 30 cm spacing, producing a disturbance zone 5 cm in width. This opener type does not require coulters or disks on the leading edge. Seeding depth varied by year because of differences in depth to moist soil, but for spring wheat ranged from 3.8 to 5 cm. Stands were excellent for all crops in all years, except for conventional tillage yellow mustard in 2001 (http://scarab.msu.montana.edu/spm/Havresite/havresite.htm) (verified 22 August 2006). Crop cultivars, planting, and harvest dates were previously provided (Lenssen et al., 2007).

All crops in 1998 followed summer fallow in 1997, and those crops scheduled for planting in 1999 that by design followed summer fallow, actually followed two consecutive years of summer fallow. Consequently, two field seasons were required for true initiation of the crop sequences, so results from 1998 and 1999 are not presented, but are available on a project website (http://scarab.msu.montana.edu/spm/Havresite/havresite.htm). Weed control was done with appropriate labeled herbicides. Weed control in spring wheat, pea, sunflower and chickpea plots was excellent from 2000 through 2003. However, control of broadleaf weeds in zero tillage safflower and lentil was poor most years. Weed control was poor in sunflower, lentil, and pea in 1999 due to lack of sufficient rainfall for herbicide activation following October 1998 applications.

2.4. Crop and soils data collection

Crop aboveground biomass was determined by clipping 1-m of row prior to seed harvest, oven drying, and weighing samples. Yield samples for all crops were taken with a self-propelled combine equipped with a 1.5 m header harvesting a 30.4 m run. Yield samples were dried, cleaned with combinations of sieves and wind, weighed, and subsampled for grain N analysis. Wheat grain nitrogen analysis was done by calibrated near infrared spectroscopy. Alternate crop seed, and biomass nitrogen for all crops, was done by combustion (Fiedler et al., 1973). Nitrogen harvest index was calculated as seed nitrogen yield/biomass nitrogen. Soil nitrate was determined by colorimetry (Mulvaney, 1996). Grain yields were reported previously (Lenssen et al., 2007) but are included in this paper to aid readers in interpretation of results.

2.5. Statistical analyses

Data were analyzed with PC-SAS using the Mixed procedure with appropriate error terms for a split-plot analysis with all treatment factors considered fixed effects. Arcsine-square root transformations were done for percentage data prior to analyses. When year or interactions with year were significant, analyses were done within years for spring wheat. For other crops, analyses were done within crop. Differences among treatments are reported at the 0.05% level of significance. Pearson correlation analyses across years were done with PC-SAS.

3. Results and discussion

3.1. Precipitation

Precipitation in 3 of the 4 years was substantially below normal (Table 1). Although 2002 received normal growing season precipitation, soil moisture was poor from planting until mid-June, when a substantial snow event occurred. Cold weather damage to crops, however, was not evident. For all years of this study, 1998–2003, long-term drought in this region of the northern Great Plains impacted crop development and production.

3.2. Spring wheat nitrogen

3.2.1. Preplant soil nitrogen availability

The effects of year, rotation, and interactions with year were significant for all crop parameters in this study except for NHI, so results are presented by year.

For all 4 years, the effect of rotation was significant on preplant residual nitrate, but not for tillage system (Table 2). Wheat following yellow mustard or chickpea was usually among the lowest for preplant nitrate concentration. Otherwise, trends in relative differences among rotations for preplant residual nitrate were not consistent among years. For instance, wheat in the F–W–P rotation was among the highest for nitrate concentration prior to planting the 2000 crop but was among the lowest in 2001–2002 (Table 2). In 2001 and 2003, recropped wheat in the F–W–W rotation was among the lowest for nitrate concentration prior to planting, but in 2000 and 2002, this crop was among the highest for preplant nitrate. The mean preplant nitrate content for wheat following summer fallow was 99 kg ha^{-1}, while that of wheat following another crop was 78 kg ha^{-1}.

Numerous studies have documented preplant nitrate levels for spring wheat in various cropping systems. Soon et al. (2001) reported that nitrate at wheat planting was influenced more by tillage system than previous crop. They found that at seeding, conventionally tilled soil had 28 kg ha^{-1} more nitrate available than did soil in zero tillage. In contrast, spring wheat received average applications of 36 and 34 kg ha^{-1} fertilizer nitrogen in conventional and zero tillage, respectively, in our trial. Additionally, and unlike Soon et al., we report that preplant nitrate was strongly influenced by rotation but not by tillage. In a 36-year trial using conventional tillage, Campbell et al. (2005) reported that wheat following fallow required less fertilization to satisfy N requirement, 17 kg ha^{-1}, than did wheat following wheat and flax, 37 and 32 kg ha^{-1}, respectively. In the 4 years of our trial, wheat in W–F rotation required 18 kg fertilizer N ha^{-1} year^{-1}, while wheat following fallow in F–W–W, F–W–safflower, and F–W–P averaged fertilizer N requirement of 24, 21 and 35 kg N ha^{-1}, respectively. Trials in Australia revealed

Table 2
Preplant residual nitrate-nitrogen, total nitrogen supply, grain N concentration in seed, nitrogen accumulation in grain and aboveground biomass, and nitrogen recovery index (0–60 cm) from spring wheat in two tillage treatments and 10 crop sequences, Havre, MT, 2000–2003[a]

Treatment	Residual nitrate (0–60 cm) (kg ha^{-1})	Total N supply (0–60 cm) (kg ha^{-1})	Grain N (mg kg^{-1})	Grain N (kg ha^{-1})	Biomass N (kg ha^{-1})	NRI[b]	Grain yield (Mt/ha)
2000							
Tillage							
Conventional	70	105	319	26	58 b	0.26	0.81
Zero tillage	81	115	317	24	71 a	0.24	0.82
Crop sequence							
W	80 ab	87	319	16 e	51 c	0.20 c	0.50 e
FW	88 a	95	311	34 ab	74 ab	0.39 a	1.13 b
LW	34 c	114	324	16 e	57 bc	0.15 c	0.54 e
F(W)W	105 a	112	313	31 bc	67 bc	0.32 ab	1.02 bc
FW(W)	95 a	101	320	19 e	55 c	0.20 c	0.60 e
FWP	98 a	105	316	39 a	88 a	0.38 ab	1.33 a
FWSaff	74 ab	111	319	32 b	74 ab	0.29 b	1.02 bc
FMW	41 c	120	327	17 e	57 bc	0.14 c	0.52 e
FCW	55 bc	134	326	26 cd	57 bc	0.20 c	0.84 cd
PWSun	86 ab	124	309	21 de	62 bc	0.20 c	0.68 de
2001							
Tillage							
Conventional	71	126	337	7	17 b	0.06 b	0.20
Zero tillage	58	113	341	9	22 a	0.08 a	0.25
Crop sequence							
W	45 de	116	340 bcd	3 e	17 c	0.02 d	0.08 e
FW	139 a	145	348 ab	18 a	38 a	0.14 ab	0.52 a
LW	75 bcd	118	324 e	1 e	6 de	0.01 de	0.04 ef
F(W)W	86 bc	117	345 ab	14 bc	30 ab	0.13 ab	0.42 bc
FW(W)	33 e	116	343 abc	3 e	10 cde	0.03 d	0.08 e
FWP	44 de	116	336 cde	13 c	28 b	0.11 b	0.38 c
FWSaff	103 b	120	342 abc	16 ab	39 a	0.15 a	0.47 ab
FMW	27 e	110	350 a	6 d	15 cd	0.05 c	0.16 d
FCW	56 cde	118	332 de	3 e	11 cde	0.03 d	0.08 e
PWSun	38 e	118	329 e	1 e	3 e	0.01 e	0.02 f
2002							
Tillage							
Conventional	92	118	346	36 b	76 b	0.31	1.04 b
Zero tillage	80	129	341	45 a	91 a	0.40	1.32 a
Crop sequence							
W	103 abc	125	359 a	34 cd	82 bc	0.29	0.94 c
FW	64 d	118	337 b	40 ab	88 bc	0.36	1.22 abc
LW	68 d	118	345 ab	43 ab	84 bc	0.38	1.27 ab
F(W)W	64 d	117	343 b	48 a	107 a	0.43	1.43 a
FW(W)	128 a	142	342 b	40 ab	76 c	0.33	1.18 abc
FWP	76 cd	134	315 c	30 d	55 d	0.25	0.97 bc
FWSaff	92 bcd	118	342 b	48 a	85 bc	0.43	1.43 a
FMW	82 bcd	118	358 a	35 bcd	83 bc	0.33	0.99 bc
FCW	80 bcd	119	346 ab	42 abc	95 ab	0.38	1.20 abc
PWSun	106 ab	125	345 ab	39 bc	79 bc	0.37	1.16 abc
2003							
Tillage							
Conventional	131	140	305	22	50	0.18	0.72
Zero tillage	107	123	301	23	58	0.22	0.77
Crop sequence							
W	153 ab	159 ab	304 ab	14 d	44 d	0.09 e	0.46 d
FW	130 abc	136 abcd	307 a	35 a	72 ab	0.29 a	1.13 a
LW	120 bcd	125 bcd	295 c	13 d	36 d	0.16 cde	0.45 d
F(W)W	165 a	170 a	306 a	32 ab	62 bc	0.22 abc	1.03 ab

Table 2 (*Continued*)

Treatment	Residual nitrate (0–60 cm) (kg ha^{-1})	Total N supply (0–60 cm) (kg ha^{-1})	Grain N (mg kg^{-1})	Grain N (kg ha^{-1})	Biomass N (kg ha^{-1})	NRI[b]	Grain yield (Mt/ha)
FW(W)	91 d	121 bcd	306 a	17 cd	48 d	0.16 cde	0.56 cd
FWP	119 bc	125 bcd	302 ab	31 ab	67 ab	0.28 a	1.05 ab
FWSaff	136 ab	144 abc	307 a	30 b	75 a	0.24 ab	0.98 b
FMW	80 d	115 cd	307 a	14 d	41 d	0.14 de	0.46 d
FCW	100 cd	122 bcd	298 bc	20 c	44 d	0.17 bcd	0.66 c
PWSun	92 d	98 d	299 bc	20 c	51 cd	0.25 ab	0.67 c
Mean annual (2000–2003)							
Tillage							
Conventional	91 a	125	327	22 b	50 b	0.20	0.69 b
Zero tillage	82 b	117	325	25 a	61 a	0.23	0.79 a
Crop sequence							
W	95 abc	122	330 ab	17 e	48 c	0.15 b	0.49 e
FW	105 a	123	325 bcde	32 a	68 a	0.30 a	1.00 a
LW	74 d	119	321 def	19 de	46 c	0.17 b	0.57 cde
F(W)W	105 a	129	327 bcd	31 a	67 a	0.28 a	0.98 a
FW(W)	87 bcd	120	328 bc	20 cd	47 c	0.19 b	0.60 cd
FWP	84 cd	120	317 f	28 b	59 b	0.26 a	0.93 a
FWSaff	101 ab	123	328 bc	32 a	68 a	0.28 a	0.97 a
FMW	57 e	116	335 a	18 de	49 c	0.16 b	0.53 de
FCW	73 de	123	324 cde	22 c	51 c	0.19 b	0.70 b
PWSun	81 cd	116	320 ef	20 cd	49 c	0.21 b	0.63 bc

[a] Means within year, tillage, or crop sequence, followed by the same letter are not different at $P < 0.05$.
[b] Nitrogen removal index (0–60 cm) = grain N (kg ha^{-1})/total N supply (kg ha^{-1}).

that soil nitrate following pea or lupine (Evans et al., 1991, 1996) and chickpea (Dalal et al., 1998) was greater for the subsequent wheat crop than nitrate content for wheat following wheat. In Saskatchewan, Canada, Gan et al. (2003) found that residual nitrate was always greater following cereal–pulse sequences compared to cereal–oilseed and cereal–cereal sequences, although differences were not significant every year.

Following the addition of N fertilizer at planting, differences for total available N among rotations and tillage systems were nonsignificant for 2000–2002 (Table 2). However, rotations varied for total available N in 2003, with continuous wheat, wheat following fallow in F–W–W, and wheat in F–W–safflower rotations having much higher available nitrogen levels than required for the yield goal. Mean available nitrogen was 124 and 119 kg ha^{-1} for spring wheat following summer fallow and other crops, respectively.

3.2.2. Spring wheat grain and biomass nitrogen

Tillage system did not produce a significant effect on grain N concentration in any year (Table 2). Our finding little impact of tillage system on grain N concentration is in agreement with results of O'Leary and Connor (1997a) and Campbell et al. (2004). Conversely, Miller et al. (2002b) reported that spring wheat grain protein concentration was higher in minimum tillage systems than for no-till.

Grain N concentration differed by crop rotation in 3 of 4 years. Among rotations, wheat following yellow mustard had the highest grain N concentration while wheat following lentil or chickpea was among the lowest in 2 of 3 years. Our results for grain N concentration of wheat following pulses contrast to those of other studies. Numerous studies have shown that wheat grain N concentration was higher following pulses than wheat, including lentil (Campbell et al., 1992; Miller et al., 2003b), chickpea (Dalal et al., 1998; Miller et al., 2003b), and pea (Evans et al., 1991; O'Leary and Connor, 1997b; Miller et al., 2003b). However, Miller et al. reported that grain N concentration (2003b) and grain protein (2002b) of wheat following oriental mustard (*B. juncea*) was higher than for wheat following wheat, similar to our results with yellow mustard. Across years, grain N concentration was 325 and 327 mg kg^{-1} for wheat following fallow and other crops, respectively.

Spring wheat grain N accumulation varied by tillage system in 2002, but it did not in other years (Table 2). In that year, zero tillage production resulted in more accumulated grain N than for conventional tillage. The effect of tillage on wheat grain N accumulation was inconsistent in other trials. In a study involving several rotations, Miller et al. (2002b) reported tillage had a nonsignificant effect on grain N yield.

The effect of rotation was significant every year for grain N accumulation. In general, wheat crops following fallow accumulated more N in grain than did recropped wheat, averaging 31 and 19 kg ha^{-1}, respectively, a result similar to that reported by Campbell et al. (1991, 2004, 2005), who found a 68% increase in grain N accumulation following fallow. For recropped spring wheat over the 4 years of our trial, wheat following chickpea accumulated more grain N than did continuous wheat and wheat following lentil or yellow mustard. Miller et al. (2002b) reported spring wheat accumulated more grain N following pulse crops, chickpea, lentil, and pea, than oilseeds. They also found wheat following wheat accumulated the least amount of grain N. Pilbeam et al. (1997) found wheat following chickpea, lentil, and fallow accumulated more grain N than continuous wheat.

Across rotations, spring wheat aboveground biomass N accumulation was higher in zero tillage production than conventional tillage for 3 of 4 years, averaging 60.5 and 50.3 kg ha^{-1}, respectively. Soon et al. (2001) reported wheat in conventional tillage had an aboveground biomass N yield 83% of that for zero tillage, the same that we report. Rotations varied each year for aboveground biomass N accumulation. For the three dry years, 2000, 2001, and 2003, wheat following fallow typically accumulated more N in aboveground biomass than did recropped wheat. Across the 4 years, N accumulation in aboveground biomass of wheat averaged 66 and 49 kg N ha^{-1} for wheat following fallow and other crops, respectively. In a 36-year trial, Campbell et al. (2005) found aboveground N yield for spring wheat following fallow or spring wheat was 77 and 54 kg N ha^{-1}, respectively. Precipitation during the first 18 years of their study, 176 mm May–August, was described as generally below average for Swift Current, SK, similar to the long-term average for Havre of 179 mm. Unfortunately during our study, precipitation averaged only 117 mm May–August, substantially lower than for other studies. In the more arid of two locations in an Australian trial, O'Leary and Connor (1997b) reported differences were not significant for aboveground biomass N among rotation, stubble, and tillage treatments, however, differences were significant for these parameters at the wetter site. In our study, zero tillage plots had higher soil residue cover. Increased soil residue cover can improve system efficiency in several ways. Increased soil residue cover can decrease water loss by evaporation, thus making more water available to soil microbes that evolve inorganic nitrogen and to the crop itself, improving overall nitrogen uptake and yield.

3.2.3. Spring wheat nitrogen use efficiency

Spring wheat NHI varied by year, tillage, and rotation, but not for their interactions (Table 3). Partitioning of N to grain was highest in 2002, the wettest year in the study. Across rotations and years, conventional tillage was more successful at partitioning N to grain than was zero tillage. Spring wheat that followed summer fallow had higher NHI than did spring wheat following other crops, averaging 0.51 and 0.38, respectively. Campbell et al. (2004) reported that NHI of spring wheat was not affected by previous crop, but was influenced by drought. Calculating NHI from published research provides conflicting results for wheat NHI. The calculated NHI from 8 years results (Dalal et al., 1998) provides identical values of 0.81 for wheat following chickpea and fallow. Conversely, calculated NHI from Campbell et al. (1992) for a 12-year study gives values of 0.70, 0.70, and 0.65 for wheat following fallow, wheat, and lentil, respectively, for nitrogen fertilized treatments. However, we cannot determine whether or not the NHI for wheat following lentil varied significantly from other treatments.

Grain NRI varied by tillage system only in 2001 (Table 2). Across years, NRI averaged 0.23 and 0.20 for

Table 3
Grain nitrogen harvest index from spring wheat grown in two tillage systems and 10 crop sequences, Havre, MT, 2000–2003[a]

Treatment	Spring wheat NHI[b]
Year	
2000	0.411 b
2001	0.393 b
2002	0.494 a
2003	0.426 ab
Tillage	
Conventional	0.458 a
Zero tillage	0.403 b
Crop sequence	
W	0.325 d
FW	0.571 a
LW	0.390 bcd
F(W)W	0.507 ab
FW(W)	0.392 bcd
FWP	0.512 ab
FWSaff	0.459 abc
FMW	0.380 cd
FCW	0.416 bcd
PWSun	0.353 cd

[a] Means within year, tillage, or crop sequence, followed by the same letter are not different at $P < 0.05$.

[b] Nitrogen harvest index = grain N (kg ha^{-1})/biomass N (kg ha^{-1}).

zero and conventional tillage systems, respectively. Rotations varied for NRI in 3 of 4 years. The NRI averaged 0.28 and 0.18 for wheat following fallow and recrop wheat, respectively. Yamoah et al. (1998) documented increasing N fertilizer rates reduced NRI for maize and concomitantly increased residual nitrate. Additionally, they found continuous maize and sorghum systems had lower NRI than did these crops when grown in rotation with other crops, a result similar to our study, where continuous wheat had the lowest 4-year mean NRI, 0.15. Regression analysis using rotation means across years for spring wheat fertilizer N application rate to predict NRI were significant (Table 2). However, the prediction of NRI with crop water use was a substantial improvement compared to that from fertilizer N rate, again showing the large effect of drought on our trial. We assume pulse crop nitrogen fixation was nominal due to the high residual nitrate levels prior to planting.

3.3. Alternate crops

Within species, alternate crops varied by year or tillage for many parameters, but year × tillage interactions were nonsignificant, so results are presented within species for tillage and years (Table 4). Seed nitrogen analyses were not done on pulses from the drought year of 2001, consequently NHI and NRI values do not include data from that year for pea, lentil, and chickpea.

3.3.1. Field pea

Because pea was present in two rotations, the effects of rotation and interactions with rotation were included in statistical analyses involving pea. However, these effects were not significant, and results presented are means across rotations. Preplant soil nitrogen was higher for pea in conventional tillage than for zero tillage (Table 4). However, tillage system did not influence seed or aboveground N accumulation, NHI or NRI. Years varied significantly for seed N accumulation but not seed N concentration. Aboveground N accumulation varied by years, with the severe drought year, 2001, having the least accumulation. Pea seed yield was only 70 kg ha^{-1} in 2001 (Lenssen et al., submitted for publication), and assuming similar seed N concentration as that reported for 3 years, seed N accumulation would have been about 3 kg ha^{-1}. Research from Syria and France (Beck et al., 1991) and New Zealand (Ayaz et al., 2004) documented superior productivity, N accumulation in seed and biomass, and NHI in well-watered environments. However, overall pea productivity and N accumulation and partitioning patterns in the dry season in Syria were similar to those reported in our study. The NRI never exceeded 1.0, and only in 1 year, the wetter season of 2002, did aboveground N accumulation surpass that of preplant available supply N. Voisin et al. (2002) documented increased mineral N availability did not increase yield or seed N concentration of pea, resulting in similar NHI across available nitrogen levels. By calculating N accumulation in seed and aboveground biomass from Voisin et al. (2002), and considering results from Beck et al. (1991), it is apparent that pea grown under well-watered conditions can accumulate substantial N in seed and biomass, three to four times greater than that found in our study conducted under drought conditions.

3.3.2. Lentil

Across years, tillage system did not influence any measured N parameter (Table 4). However, the effect of year was significant for available soil nitrogen and aboveground biomass N accumulation. Lentil did not yield seed in 2000, and seed produced in 2001 were not analyzed for N, so NHI and NRI values do not include those years. However, calculated seed N based on lentil yield in 2001 (Lenssen et al., 2007) and mean seed N concentration from 2002 to 2003, seed N accumulation would have been less than 1 kg N ha^{-1}, an insignificant amount. Previous research has shown seed N concentration of lentil at about 400 mg kg^{-1} (Campbell et al., 1992; Whitehead et al., 2000) under well-watered conditions, but seed N was elevated in a drier environment (Beck et al., 1991). Aboveground accumulation of biomass N varied by years, with 2002 having the highest value, however values were substantially less than those reported in the aforementioned studies with lentil. Biomass N accumulations never surpassed available soil nitrogen levels, indicating that nitrogen fixation was likely insignificant in this trial. Overall, our results strongly indicate that planting of lentil during moderate to severe drought is inadvisable.

3.3.3. Chickpea

For chickpea, the effect of tillage was significant for seed N concentration and accumulation (Table 4). Seed N concentration was higher in conventional tillage but seed N accumulation was higher in zero tillage. In a study conducted under drought conditions, seed N accumulation for chickpea was higher in zero tillage compared to conventional tillage (Horn et al., 1996). However, in a study conducted under well-watered

Table 4
Preplant residual nitrate-nitrogen, total nitrogen supply, grain N concentration in seed, nitrogen accumulation in grain and aboveground biomass, nitrogen harvest index, and nitrogen recovery index (0–60 cm) from six alternate crops in rotation with spring wheat in two tillage treatments, Havre, MT, 2000–2003[a]

Treatment	Residual nitrate ($kg\ ha^{-1}$)	Total N supply ($kg\ ha^{-1}$)	Seed N ($mg\ kg^{-1}$)	Seed N ($kg\ ha^{-1}$)	Biomass N ($kg\ ha^{-1}$)	NHI[b]	NRI[c]	Yield
Pea								
Tillage								
Conventional	88 a	94 a	495	42	59	0.613	0.574	0.66
Zero tillage	66 b	72 b	490	47	60	0.699	0.711	0.74
Year								
2000	76 b	83 b	494	23 b	71 b	0.343 c	0.360 b	0.48 b
2001	50 b	56 b	–	–	18 c	–	–	0.07 c
2002	69 b	75 b	493	56 a	90 a	0.639 b	0.900 a	1.15 a
2003	112 a	118 a	491	55 a	58 b	0.984 a	0.668 ab	1.11 a
Lentil								
Tillage								
Conventional	89	100	510	9	43	0.145	0.163	0.28
Zero tillage	85	95	505	10	40	0.158	0.067	0.13
Year								
2000	80 b	86 b	–	–	54 a	–	–	0.00
2001	31 c	37 c	–	–	10 b	–	–	0.01
2002	149 a	155 a	464	18	82 a	0.263	0.215	0.72
2003	87 b	111 ab	552	1	21 b	0.040	0.015	0.01
Chickpea								
Tillage								
Conventional	108	111	502 a	18 b	54	0.342	0.079	0.25 b
Zero tillage	97	100	481 b	28 a	60	0.425	0.121	0.41 a
Year								
2000	87 b	94 b	–	–	72 a	–	–	0.00
2001	92 b	98 b	–	–	27 c	–	–	0.01 c
2002	78 b	84 b	461 b	33 a	58 b	0.590 a	0.416 a	0.73 a
2003	153 a	159 a	522 a	13 b	70 ab	0.179 b	0.100 b	0.25 b
Yellow mustard								
Tillage								
Conventional	112	146	631	18	34 b	0.398	0.147	0.26
Zero tillage	97	132	615	15	52 a	0.235	0.147	0.27
Year								
2000	89 b	96 c	601 b	24 a	–	–	0.286 a	0.41 a
2001	66 b	144 ab	649 a	15 b	48	0.320	0.106 b	0.23 b
2002	87 b	135 b	649 a	23 a	53	0.461	0.174 b	0.31 ab
2003	175 a	180 a	593 b	4 c	28	0.171	0.021 c	0.09 c
Safflower								
Tillage								
Conventional	87	101	325	4 a	25	0.125	0.043	0.10
Zero tillage	72	86	322	2 b	27	0.070	0.033	0.05
Year								
2000	94 ab	100	321	1 b	53	0.025 b	0.011 b	0.03 b
2001	35 c	73	310	1 b	8	0.200 a	0.019 b	0.04 b
2002	91 b	97	316	9 a	–	–	0.113 a	0.20 a
2003	99 a	104	346	1 b	196	0.068 b	0.009 b	0.03 b
Sunflower								
Tillage								
Conventional	92	106	395	3	39	0.041	0.051	0.05
Zero tillage	82	96	411	3	40	0.032	0.020	0.18
Year								
2000	91 a	97 ab	403	3	70 a	0.036	0.036	0.06
2001	26 b	63 b	–	–	16 b	–	–	0.00

Table 4 (*Continued*)

Treatment	Residual nitrate ($kg\ ha^{-1}$)	Total N supply ($kg\ ha^{-1}$)	Seed N ($mg\ kg^{-1}$)	Seed N ($kg\ ha^{-1}$)	Biomass N ($kg\ ha^{-1}$)	NHI[b]	NRI[c]	Yield
2002	128 a	133 a	–	–	–	–	–	0.35
2003	103 a	109 a	–	–	32 b	–	–	0.00

[a] Means within crop, year, or tillage followed by the same letter are not different at $P < 0.05$.
[b] Nitrogen harvest index = grain N ($kg\ ha^{-1}$)/biomass N ($kg\ ha^{-1}$).
[c] Nitrogen removal index (0–60 cm) = grain N ($kg\ ha^{-1}$)/total N supply ($kg\ ha^{-1}$).

conditions, López-Bedillo et al. (2004) reported conventional tillage production accumulated more seed N compared to zero tillage. Chickpea had no harvestable yield in 2000, and seed produced in 2001 were not analyzed for N, so NHI and NRI values do not include those years. Other studies report superior nitrogen partitioning to grain compared to our study (Beck et al., 1991; Ayaz et al., 2004; López-Bedillo et al., 2004). The severe drought year of 2001 had the lowest aboveground N accumulation. Due to elevated soil nitrate levels and drought, nitrogen fixation likely was poor during our study (Dalal et al., 1997; Schwenke et al., 1998).

3.3.4. Yellow mustard

The effect of tillage was not significant for any parameter measured, except accumulated N in biomass (Table 4). Mustard production with zero tillage resulted in more N accumulated in aboveground biomass but less efficient partitioning of N to seed compared to conventional tillage. Years varied for available soil nitrogen, seed N concentration and accumulation, and NRI. Seed yield was negligible in 2003 when flea beetles (*Phyllotreta cruciferae* Goeze) killed most emerging seedlings from the initial 30 April planting date. The combination of a replanted crop and elevated air temperatures at flowering resulted in poor seed set. Yellow mustard biomass samples were not collected in 2000, and biomass N and NHI do not include data from that year. In our trial, productivity of yellow mustard was similar to that reported by O'Connell et al. (2002), 0.27 and 0.22 $Mg\ ha^{-1}$, respectively, substantially less than reports of cool-season oilseed production in other trials in the northern Great Plains (Miller et al., 1998, 2003b; as reviewed in Johnston et al. (2002)). Overall, yellow mustard productivity was low, and this crop was not well adapted to the intensity of drought experienced during our trial.

3.3.5. Safflower

Across years, safflower in conventional tillage accumulated more N in seed, the only parameter measured that was significant for tillage (Table 4). However, seed N accumulation was very low for both tillage systems, substantially below that reported by Nasr et al. (1978, reported as protein yield) and Koutroubas et al. (2004). Years varied for preplant soil nitrate, NHI and NRI. Bassil et al. (2002) documented the excellent residual soil nitrate scavenging by safflower, particularly to depths of 125 cm. In our study, however, soil moisture was quite limiting and safflower accumulated little nitrogen, except in 2003. Koutroubas et al. reported significant variation by year for NHI and biomass N accumulation, along with genotype and genotype × year interactions. Safflower biomass samples were not collected from conventional tillage plots in 2002, and analyses of biomass N accumulation and NHI did not include data from that year. Results show that safflower is not adapted to the level of drought that occurred during the course of this study. Aase and Pikul (2000) concluded that safflower was poorly adapted to the northern Great Plains because its intensive water use causes poor productivity of the subsequent crop due to very low soil water availability, unless a season of summer fallow is included for soil water recharge. Miller et al. (2002b) suggested that safflower was poorly adapted to the Canadian prairie of the northern Great Plains compared to cool-season pulse and oilseed crops. Our results agree with Aase and Pikul and Miller et al.; safflower is poorly adapted to the northern Great Plains, especially during periods of drought.

3.3.6. Sunflower

Sunflower was poorly adapted to the intensity of drought encountered during this study. Sunflower did not produce seed in 2001 or 2003 due to drought, and only one plot produced seed in 2002, primarily due to pronghorn (*Antelocapra americana*) browsing of flower buds. Thus N parameters related to seed yield were only available from 2000. For that year, the effect of tillage on grain N parameters was not significant (Table 4). Results were available for preplant available nitrogen from all years, and the effect of year was significant, however, the influence of tillage was not. Several published trials provide results on plant N concentrations and partitioning of N, and their variability over years (Zubillaga et al., 2002; Montenmurro and De Giorgio, 2005), but we are not aware of any published trial involving sunflower that was conducted under such extreme drought conditions. Despite having significantly higher seed yields than those of our trial, Miller et al. (1998) concluded sunflower 'Sunola' was not well adapted to the southern regions of the Canadian prairie in Saskatchewan, in part due to its low grain yield and WUE_{grain} compared to pulse and cool-season oilseeds. Norwood (2000) and Aase and Pikul (2000) also reported soil water contents were very low following sunflower harvest, leaving the subsequent crop more prone to significant drought stress if soil water recharge was insufficient. Results from our trial show that sunflower was not adapted to the northern Great Plains during drought.

3.3.7. Correlations of crop nitrogen with water use

Correlations of water use with grain N concentration and accumulation, aboveground N accumulation, NHI and NRI were positive and significant for spring wheat (Table 5). For field pea, correlations with water use were positive and significant for seed and biomass N accumulation, NHI, and yield, but the correlation with straw N was negative and significant. Correlations of chickpea water use with NHI, NRI, and yield were positive and significant, but correlations with straw N accumulation and grain N concentration were negative. Results for lentil were similar to those of pea and chickpea, with water use positively correlated with biomass N accumulation, NHI, and yield, and grain N concentration negatively correlated. Safflower water use was positively correlated with grain N accumulation, NRI and yield. For yellow mustard and sunflower, all correlations of water use with soil or plant N parameters were nonsignificant.

In our study, rotational and seasonal effects were generally more important for spring wheat N accumulation in grain and biomass, NRI, grain yield, water use, harvest index, and WUE_{grain}, than tillage system (Lenssen et al., 2007), similar to results of Halvorson et al. (2002) and Latta and O'Leary (2003). Other studies have reported substantially higher amounts of water capture in zero tillage systems compared to tilled fallow. O'Leary and Connor (1997a) documented water capture differences between zero tillage and conventional tillage systems became smaller with decreasing rainfall, while Halvorson et al. (2002) documented yield differences among tillage systems were minimal during years with less than 300 mm annual precipitation in North Dakota, USA.

The adoption of zero tillage has led to more recropped acres in the Great Plains, with a concomitant reduction in summer fallow acreage. Across 10 rotational sequences and 4 years, zero tillage wheat averaged higher grain and aboveground biomass N accumulation than did conventional tillage wheat. However, differences between tillage systems were nonsignificant for NRI. Zentner et al. (2002) determined continuous cropping and zero tillage systems were more risky and less profitable in the drier Brown and Dark Brown soil zones of the Canadian prairies than systems utilizing tillage and summerfallow.

There is no single parameter that adequately measures NUE but instead several parameters should be considered. In our study, regardless of the previous crop, pulse, oilseed, or wheat, wheat following summerfallow averaged greater N accumulations in grain and biomass, and had superior NRI, strongly indicating superior NUE for wheat following summerfallow. Huggins and Pan (2003) reported large and highly variable effects of cropping system and climate on NUE. Our study was conducted in a semi-arid environment during drought, and few cropping systems studies examining NUE have been reported from

Table 5
Correlation coefficients (r) of plant nitrogen variables with water use of seven crops

Crop	Grain N (mg kg^{-1})	Grain N (kg ha^{-1})	Biomass N (kg ha^{-1})	Straw N (kg ha^{-1})	NHI[a]	NRI[b]	Yield (kg ha^{-1})
Wheat	0.15**	0.76***	0.65***	0.44***	0.21***	0.59***	0.71***
Pea	−0.02	0.65***	0.51***	−0.54***	0.65***	0.21	0.80***
Chickpea	−0.69**	0.45	0.27	−0.65***	0.54*	0.54*	0.78***
Lentil	−0.93***	0.46	0.58***	0.63	0.64*	0.41	0.47**
Mustard	−0.24	0.18	−0.13	−0.04	0.13	0.14	−0.17
Safflower	0.11	0.76***	0.16	0.11	−0.14	0.77***	0.60***
Sunflower	−0.03	−0.23	−0.09	0.62	−0.36	0.05	0.31

*, **, and *** denote significance at 0.05, 0.01, and 0.001 probability levels, respectively.
[a] Nitrogen harvest index = grain N (kg ha^{-1})/biomass N (kg ha^{-1}).
[b] Nitrogen removal index (0–60 cm) = grain N (kg ha^{-1})/total N supply (kg ha^{-1}).

environments as dry as experienced during our study. Campbell et al. (2004) stated aboveground N yield was like most yield factors, a function of available water in the northern Great Plains, and this is an appropriate description of our results.

4. Conclusions

This study was conducted during a severe, region wide drought, and nitrogen utilization efficiency of spring wheat and alternate crops in systems with or without summer fallow was poor. Preplant soil water contents were higher following summer fallow than for any crop, and spring wheat responded to this additional water better than chickpea or yellow mustard, the only other crops in the trial following summer fallow. Field pea generally performed best of all alternate crops, utilizing nitrogen as well as spring wheat following fallow. Chickpea, lentil, yellow mustard, safflower, and sunflower did not perform as well as pea or wheat, and were not adapted to this region during drought.

Research to intensify and diversify the cereal-fallow system has been conducted in semi-arid regions throughout the world. Replacing summer fallow with pulse and oilseed crops has been successful in Asia, Australia, and North America, particularly when precipitation occurs with adequate timing and quantity. Unfortunately, semi-arid zones are prone to cyclical droughts, resulting in crop failure over extensive areas, especially for continuous cropping systems in areas that average 350 mm or less precipitation per year. Summer fallow was widely adopted in Northern Plains cropping systems, in part, to stabilize wheat yields. Summer fallow likely will continue to be practiced in the drier regions of the Northern Great Plains, even in growing seasons with precipitation levels sufficient for recropping pulse and oilseed crops. Our results document that development and utilization of rotations coupling summer fallow, wheat, and annual pulse crops, such as fallow–spring wheat–pea, can help stabilize crop yields and improve overall system nitrogen use efficiency.

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